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MULTILEVEL RESONANCE ANALYSIS OF ⁵⁹Co NEUTRON TRANSMISSION MEASUREMENTS

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Abstract: Large discrepancies exist between the high-resolution ⁵⁹Co neutron transmission data of Harvey et al. and the resolved resonance parameters of ENDF/B-VI. In order to provide new resonance parameters consistent with these data, the high-resolution transmission measurements have been analyzed with the computer code SAMMY. Results of that analysis are reported here.

(⁵⁹Co transmission measurements, R-matrix analysis, resonance parameters)

Introduction

The resonance parameters describing the low-energy neutron cross sections of ⁵⁹Co are of considerable interest, not only because ⁵⁹Co is used as a structural material in nuclear technology but also because the thermal capture cross section and the capture resonance integral of ⁵⁹Co are widely used as standards and for dosimetry [1].

High-resolution neutron transmission measurements through several thicknesses of ⁵⁹Co were performed in 1986 at the Oak Ridge Electron Linear Accelerator (ORELA), in conjunction with the ENDF-B-VI evaluation of ⁵⁹Co done at Argonne National Laboratory. These measurements have much better resolution than previously published measurements [2,3]. The results of one of these measurements were used in the ENDF/B-VI evaluation of the ⁵⁹Co total cross section above 100 keV [4,5], but the data were not used below 100 keV where the ENDF/B-VI cross sections are represented by resolved resonance parameters based on a recent compilation of Mughabghab et al. [6].

The ENDF/B-VI resolved resonance parameters were used to compute values of transmission on the same energy scale as the ORELA transmission measurements; large discrepancies were observed between the computed and measured transmissions, indicating that the ENDF/B-VI resolved resonance parameters were inadequate. Therefore, all six transmission measurements were analyzed using the Reich-Moore approximation option in SAMMY [7], and new resonance parameters were obtained which are consistent with both the high resolution ORELA transmission measurements and the thermal cross sections.

In the next section of this report the experimental conditions of the ORELA transmission measurements are given, and it is shown that the ENDF/B-VI resolved resonance parameters are inconsistent with the results of these measurements. In the last section the resonance analysis with the code SAMMY is described and the new resolved resonance parameters are discussed.

The High Resolution Transmission Measurements

In 1986 a series of high-resolution transmission measurements was performed at ORELA through several thicknesses of ⁵⁹Co and under various resolution conditions, partly at the request of A. B. Smith for the ENDF/B-VI evaluation [4,5]. Only one of these measurements was processed at the time: Run 10454TS. This run was done with a very thick sample, 0.3 atoms/barn, at a flight path of 200 m and with the collimation selecting the unmoderated photoneutrons produced in the Ta target. This run is mostly useful at high energy and indeed was used only to define the total cross section above 100 keV in ENDF/B-VI.

All six runs have now been reduced to transmission versus energy. The experimental parameters for these runs are summarized in Table 1. Two of the runs with sample thicknesses of 0.3 and 0.075 atoms/b used a flight

path of 200 m with the collimation looking at the unmoderated neutrons from the Ta target; the remaining four runs used a flight path of 80 m looking at the water moderator, and samples varying in thickness from 0.005 to 0.3 atoms/barn. The samples were kept at the physical temperature of 293 K; for a Debye temperature of ⁵⁹Co of 445 K, the effective temperature is computed as 330 K. All these runs have considerably better time resolution than the previously published transmission measurements [2,3,8].

Table 1. Experimental Parameters of the Transmission Measurements

Run No.	Flight Path (m)	Sample Thickness (atoms/b)	Detector	Collimation	Linac burst width
10454TS	201.575	0.3008	NE-110	Unmoderated Ta target	5-6 ns
10460TS	201.575	0.0750		Unmoderated Ta target	5-6 ns
10432T1	80.394	0.3008	⁶ Li glass	Water moderator	12 ns
10432T2	80.394	0.0750		Water moderator	
10428T1	80.394	0.0210		Water moderator	
10428T2	80.394	0.0050		Water moderator	

In order to test the validity of the ENDF/B-VI resonance parameters, the transmission for the sample thicknesses used in the measurements were computed with these resonance parameters and with the code SAMMY, using the "no fit" option of the code. Comparisons of these computed transmission ratios with the measurements showed rather large discrepancies, indicating that the ENDF/B-VI resonance parameters were inadequate.

Figure 1 shows a comparison between the computed transmission ratio (dashed line) and the measurement of run 10432T1 (see Table 1) in the neutron energy range 2 to 3 keV. The small resonance at 2.28 keV is not in ENDF/B-VI, probably because it is too weak to have been detected in previous transmission measurements, which had poorer resolution. The resonance at 2.85 keV has clearly wrong parameters, perhaps the result of a typographical error. The resonance parameters of ENDF/B-VI were taken somewhat literally from Ref. 6, and indeed the parameters of the resonance at 2.86 keV are as given in that reference (neutron width of 3.497 eV, capture width of 0.11 eV). However, in ENDF/B-V as well as in previous evaluations [9-11] or in previous editions of the neutron cross-section compilation BNL-325 [12], the neutron width of that resonance is always given as approximately 0.1 eV. The source of the error in Ref. 6 and in ENDF/B-VI was not traced further.

Figure 2 shows a comparison between the transmission ratio computed with ENDF/B-VI (dashed line) and

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Fig. 1. ORELA data (crosses) vs transmission computed from ENDF/B-VI resonance parameters (dashed curve) and from parameters found in this work (solid curve), from 2 to 3 keV.

Fig. 2. ORELA data (crosses) vs transmission computed from ENDF/B-VI resonance parameters (dashed curve) and from parameters found in this work (solid curve), from 60 to 70 keV.

the measurement of run 10454TS over the neutron energy range from 60 to 70 keV. The figure illustrates the large discrepancies typical above 60 keV. The origin of these discrepancies could not be completely explained; in that energy region the resonance parameters published in Refs. 2 and 3 are inconsistent and ENDF/B-VI is not consistent with either of these references.

Because of these discrepancies between the experimental measurements and the calculations based on ENDF/B-VI, it was decided to analyze the six ORELA transmission measurements, using the Reich-Moore approximation and the resonance analysis code SAMMY. The assumptions of this analysis and its results are the subject of the next section.

Resonance Analysis of ^{59}Co Transmission Data

The spin J of most resonances and the orbital angular momentum ℓ for the smaller resonances cannot be determined from the data and were assigned somewhat arbitrarily as follows: (1) All the observed resonances were assumed to be due either to s -wave or to p -wave neutrons, a reasonable assumption. (2) Those resonances for which the neutron width divided by the square root of the neutron energy was larger than $0.1\sqrt{\text{eV}}$ were taken to be s -wave resonances; in many cases, the characteristic s -wave interference pattern between resonance and potential scattering can be observed. (3) Most s -wave levels were assigned a spin consistent with the assignment of Ref. 6, and therefore with ENDF/B-VI. (4) Some smaller resonances were also taken to be s -wave; these were selected so as to satisfy the long-range level-spacing correlation implied by the Dyson-Methia Δ_3 statistics [13].

(5) Since ^{59}Co has a spin of $7/2$, the interaction with p -wave neutrons can lead to the resonance spin $J = 2, 3, 4$, or 5 ; however, for simplicity, all p -wave resonances were arbitrarily assigned spins of 3 or 4 , as was also done in ENDF/B-V and ENDF/B-VI. All p -wave spin states were included in generating the potential scattering.

The neutron widths of ten large resonances above 100 keV were adjusted to account for the contribution below 100 keV of all the levels above that energy. Similarly, the parameters of four fictitious-bound levels were adjusted to account for the contribution of the bound levels and to reproduce the evaluated cross sections in the thermal region. The parameters of the first resonance, at 132 eV, were not searched, because these parameters are well known and because the ORELA transmission measurements were not optimized for that low-energy range.

The scattering length was determined from the fit to the transmission and a value of 6.67 fm was obtained, in good agreement with the value 6.80 ± 0.70 fm given in Ref. 6. The set of resonance parameters obtained is consistent with the ORELA transmission measurements, as illustrated by the solid curves in Figs. 1 and 2, which show that the resonance parameters obtained here are more consistent with the measurements than are the ENDF/B-VI parameters. The value of χ^2 per degree of freedom for each of the data sets analyzed is close to unity, also indicating consistency between the resonance parameters and the measurements.

Figures 3 and 4 illustrate graphically the agreement between the measured transmission ratios and the calculations with the resonance parameters obtained in this

Fig. 3. Measured and computed transmission through 0.005 atom/barn (upper curve) and 0.3 atom/barn (lower curve) of ^{59}Co between 20 and 40 keV. The solid lines are computed with the resonance parameters obtained in this analysis.

Fig. 4. Measured and computed transmission through 0.3 atom/barn of ^{59}Co between 70 and 90 keV. The solid line is computed with the resonance parameters obtained in this study.

study. In Table 2 the statistical properties and thermal parameters of the present evaluation are compared to the ENDF/B-VI values.

Table 2. Comparison of the present evaluation with ENDF/B-VI

	This study	ENDF/B-VI
Number of <i>s</i> -wave levels	80	117
$\langle \Gamma_n^0 \rangle$ (eV)	0.941	0.8226
$\langle \Gamma_\gamma \rangle$ (eV) for $\ell = 0$	0.4488	0.4445
Average <i>s</i> -wave level spacing (eV)	1299	1034
<i>s</i> -wave strength function	3.83×10^{-4}	3.93×10^{-4}
Number of <i>p</i> -wave levels	65	1
$\langle \Gamma_n^0 \rangle$ (eV)	0.237	2.806
$\langle \Gamma_\gamma \rangle$ (eV) for $\ell = 1$	0.36	0.37
Average <i>p</i> -wave level spacing (eV)	1562.5	
<i>p</i> -wave strength function	0.25×10^{-4}	
Cross sections at 0.073 eV		
σ_t (b)	43.150	43.143
$\sigma_{n\gamma}$ (b)	37.170	37.190
σ_a (b)	5.980	5.953
Westcott g_γ factor	1.0000	1.0019
Channel radius (10^{-12} cm)	0.6672	0.620
Capture resonance integral (b)	75.74	75.72

The transmission measurements are not very sensitive to the value of the capture widths; therefore, the capture widths obtained in this analysis have large uncertainties. An attempt was made to adjust the capture widths to give the capture areas reported by Spencer et al. [14,15]; however, the attempt was not successful because the correspondence between the resonances observed in transmission and those reported with the capture measurements are not unambiguous; many multiplets are not resolved in the capture measurements. The problem is complicated by the large (20 to 40%) multiple scattering corrections that were made by Spencer et al. on the capture areas which had to assume prior values of the resonance parameters. A direct analysis of capture data with the code SAMMY cannot be done until SAMMY is modified to handle multiple scattering effects, an effort which is currently underway.

The capture cross section averaged over intervals from 1–100 keV is given in Table 3 to facilitate future evaluation work. The average capture cross section at 30 keV (averaged from 23–37 keV) is 36.9 mb, compared with 88 ± 30 mb of Gibbons et al. [16] and 48 ± 5 mb from Stroud et al. [17]. The average capture from 85–100 keV is 15.3 mb, compared with 18.0 ± 0.6 mb given by Spencer and Macklin [15] over that energy interval.

Table 3. Averaged capture cross section

Energy interval (keV)	Cross section (mb)
1 – 10	88.8
10 – 20	32.1
20 – 30	35.9
30 – 40	27.3
40 – 50	16.7
50 – 60	19.9
60 – 70	19.6
70 – 80	18.5
80 – 90	14.7
90 – 100	15.8

Conclusions

The investigations described in this report indicate that the representation of the neutron interactions with ^{59}Co in ENDF/B-VI is unsatisfactory below 100 keV, although the thermal cross sections are correctly reproduced. Indeed ENDF/B-VI fails to describe properly the

most recent ORELA transmission ratio measurements. These transmission measurements were analyzed with the resonance analysis code SAMMY and a set of resonance parameters was obtained that is consistent with those transmission measurements. These resonance parameters are a dramatic improvement over ENDF/B-VI. An additional improvement could be achieved by the analysis of relevant capture measurements. Such an analysis would require a treatment of multiple scattering not yet available in the resonance analysis code SAMMY. The resonance parameters obtained from this work, together with the previously determined parameters of the 132-eV resonance, provide an accurate total cross section from 10^{-5} eV to 100 keV. The capture cross section is reproduced at thermal. Further analysis of the capture data from 132 eV to 100 keV is warranted.

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